

PNEUMOPULSE TECHNOLOGY FOR INDUSTRIAL APPLICATIONS

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Abstract

New approach of short-duration gasdynamic devices using for industrial applications is described. In common all pneumopulse technologies are based on the short impact of the powerful air jets, which are created with the help of special pneumatic pulse generator. Some examples of developed technologies which have been successfully used in practice confirm effectiveness of chosen method.

Key words: *pneumopulse device, technology, air shock wave, powerful gas jet, deposit cleaning*

1. INTRODUCTION

At the Khristianovich Institute of Theoretical and Applied Mechanics (Siberian Branch of Russian Academy of Sciences) a variety of gas dynamic pulsed devices were developed and used for several decades [1-2]. They should create a pulsed gas flow with the specified values of temperature and pressure that exists within a very short period of time (less than 0.1 seconds). Such a short period of time, on the one hand, significantly reduces the complexity and cost of construction, and on the other hand, it can achieve extremely high flow parameters, which impossible to obtain in known devices of stationary action. For example, in pulsed devices the gas flow rate of tens or hundreds of pounds can be easily obtained, that can only be achieved by superpower compressor plants [3].

These unique properties of pulse gas-dynamic devices developed served as a starting point for creating a number of pneumopulse technologies of general application. They have found application in various branches of the economy and, in particular, to create highly effective systems for impulse cleaning of technological equipment [4-5]. Common feature of all pneumopulse technologies is the use of short-term effects of shock-wave high-power impulse air jet that is created by means of special pneumopulse generators of various designs. Pneumatic generator is filled with compressed air for a few seconds and then the air is throwing during a few milliseconds in the form of high-power pulsed jets. This provides a huge air flow rate and powerful destructive pulse jet influence.

The main features of pulsed gas jets that determine the prospects for their use in industrial and technological processes:

- a range of energy stored up to 10 MJ;
- specific consumption of the working gas up to 100 kg/s;
- a wide range of impact intensity regulation;
- the technical simplicity of execution units;
- a small amount of materials and low power consumption;
- simple operation and automation possibilities.

The main directions of industrial application of impulse jets:

- intensification of technological processes;
- destruction of the becomes caked bulk materials;
- cleaning and removing of technological deposits.

The main advantages of pneumopulse technologies:

- a large range of impact intensity adjusting;
- high reliability and safety of using due to simplicity of construction;
- elementary manual or automatic control;
- no dangerous effects on the equipment because of the short pulse duration;
- absence of dust formation because of the small amount of exhaust air;
- possibility of operation in potentially explosive conditions, such as in coal bunkers.

At the ITAM SB RAS systematic studies in the following areas of pneumopulse technologies are carried out [6]:

1. Development of gaseous jet impulse generator design principles:

- analysis of arising situations, the development of approaches to the selection of the required parameters of impulsive action depending on the particular technological problems;
- creation and generalization of impulse generator design techniques and their individual elements with prescribed technical characteristics;
- development of codes for calculation unsteady gas-dynamic and mechanical processes inside pulse generators;
- development of forecasting methods and experimental studies of produced generators characteristics.

2. The study of shock waves and unsteady gaseous jets formation and propagation:

- study of the propagation and damping of shock waves in homogeneous and heterogeneous mediums, as well as on the surfaces of their partition;
- creation of computational methods for estimating the parameters of shock waves during their propagation;
- development of experimental methods for investigation of shock wave characteristics;
- investigation of transition from non-stationary shock waves to expiration of steady gas flowing.

3. Investigation of the characteristics of various materials behaviour under impulse loading:

- study of approaches for description of the stress state of various materials;
- creation of behaviour models for the various materials under impulse loading;
- development of experimental techniques for studies of materials behaviour under impulse action;
- experimental study of fracture processes of various materials under impulse action.

4. Testing of the real technological processes with the use of pulsed gas jets:

- consideration of possibilities for improving of technological processes with pulsed gas jets using;

- optimization of the characteristics of impulse device used;
- definition of real improvement in the technical and economic performances when implementing pneumopulse technology.

In this paper some results on mentioned research directions are discussed and some examples of the real pneumopulse technologies are given.

2. EXPERIENCE IN THE DEVELOPMENT OF FAST-ACTING PNEUMATIC DEVICES

2.1 The main schemes of pneumopulse devices

Pneumopulse device is intended to create a single impulse gas jet. Due to the lack of established terminology in the literature such devices are called by different names: pneumopulse generators (PPG), pneumogenerators (PG), shock wave generators (SWG), or simply generators [7].

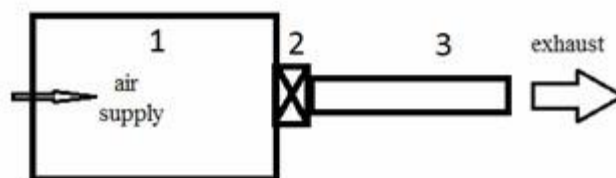


Fig. 1. Schematic diagram of the pneumopulse generator

Each pneumogenerator (see Fig. 1) contains a storage tank, a quick acting valve 2, which provides a periodic discharge of compressed air from the accumulator, and an exhaust nozzle 3, intended to direct the pulsed jet of compressed air on the cleaned surface. Dimensions of storage tank are determined by the desired duration of impulse jet. A review of different pulse generators from different manufacturers is shown that the volume of storage tank does not exceed 500 dm³ and in general ranges from 10 to 100 dm³. Compressed air at a pressure of 0.4 MPa to 1.0 MPa is typically used as a working agent for pneumopulse generators. A stationary (technological) system of the compressed air supply or specially installed compressors can be applied as a source of compressed air. The design of storage tank is performed in accordance with the rules of pressure vessels design and manufacture. Storage tank is connected to the supply line of compressed air with stop and regulating armature and means of measuring and control.

As a high-speed valve two types of valves can be used: membrane type (Fig. 2) or piston type (Fig. 3). In the generator with the membrane valve a rubber membrane 2 between the storage tank 1 and the exhaust nozzle 3 is located. The diameter of the membrane exceeds the diameter of exhaust nozzle 3 of 150-200 mm. A rubber-and-canvas material usually is used for membranes manufacture. It is recommended to use the material of the conveyor belt of high heat resistance when surfaces of high-temperature heater are cleaning. In the centre of a membrane typically reinforced metal disk is mounted, which serves to increase the reliability of the central part. When storage tank is filling then the air is simultaneously is fed into the space in front of the membrane. Because of the areas difference the membrane sags and blocks access to the nozzle. For the operation of the device the auxiliary (control) valve 4 opens and discharges the air before the membrane into atmosphere. Now, the difference in pressure causes the membrane opens the nozzle outlet and releases working gas from the storage tank in a form of impulse jet.

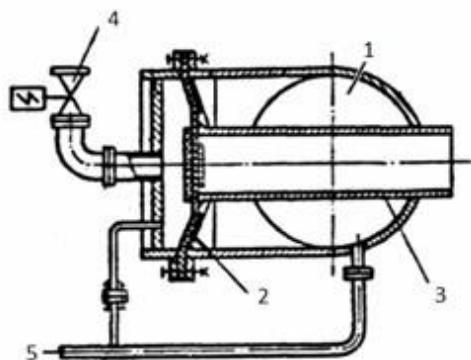


Fig. 2. Pneumopulse generator with the membrane type valve

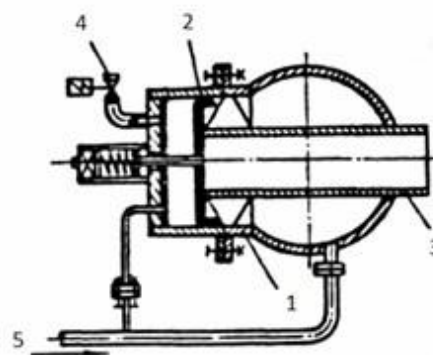


Fig. 3. Pneumopulse generator with the piston type valve

The generator with the valve of piston type (see Fig. 3) consists of a storage tank 1, moving piston 2 and the exhaust nozzle 3. Diameter of the piston 2 is selected up to 50-150 mm larger than the diameter of the exhaust nozzle 3. As in the previous case, when storage tank is filling by air, the space before the piston is fed at the same time. Due to differences in the areas piston moves to the right and blocks access to the nozzle. In order to switch the device an auxiliary (control) valve 4 opens, which discharges air from the space before the piston into the atmosphere. Now, the difference in pressure causes the piston 2 to move left and opens the nozzle. After that, a release of gas from the storage tank forms a working jet. Valves of the piston type have a number of technological advantages, why they are regarded by the author as the main direction in the design of pneumopulse generators.

A number of modern high-energy and intensive industrial processes require the use of high-speed valve, designed for high flow rate and high working gas pressure. A short time of opening can significantly reduce the complexity and cost of pneumatic devices with extremely high gas flow parameters generated, which cannot be obtained in similar devices of stationary action. Reliable fast-acting valves will allow improving the well-known technological processes, or even creating entirely new pneumopulse technology. However, such valves are not commercially available. Moreover, the dynamic characteristics of the existing pneumatic valves are not considered in the normative literature. Development and design of high-speed pneumatic devices are performed, usually, on an intuitive level due to the complexity of the implementation of qualified theoretical or experimental analysis of no stationary gas-dynamic and mechanical processes that occur inside such devices [8-9].

The author was directly involved in the development of designs of pneumatic valves with bore from tens to hundreds of millimetres, designed for the working gas pressure of several atmospheres to thousands of atmospheres, the response time which was a few milliseconds only. The accumulated experience allows formulating general principles for design and development of high-speed valves, which are described below.

2.1 The main schemes of pneumopulse devices

In the thermodynamics processes are usually considered with constant mass of working gas and, therefore, the time factor is ignored, thus it is considered that the main processes are not directly connected with the time. A characteristic feature of high-speed pneumatic devices is the fact that all internal cavities of the device are continuously exchanged through the gas lines with the atmosphere or other cavities and, consequently, the masses of gas in the inner cavities are constantly changing. Therefore, the calculation of processes in pulse devices must take into account the variable mass of

gas in this volume and variable energy that is supplied with the incoming gas and is removed out with exhaust gas (see [10-11]).

For the volume of gas with variable mass the first law of thermodynamics can be written as:

$$dQ + I_p dm_p + Idm = dU + dL \quad (1)$$

where dQ is meant by the amount of heat supplied (or allocated) from the environment;

I_p and I – are respectively the enthalpy of the entering and escaping gas;

dm_p , dm - the amount of gas supplied to the volume considered and following from it.

Given the hypothesis of quasi-stationary the rate of gas flowing in and out dm_p and dm can be calculated by the usual formula $dm = Gdt$, for steady flow over a time interval dt . The equation for calculating the average pressure in the volume of gas with variable mass can be written as follows [11]:

$$\frac{dP}{dt} = \frac{k-1}{V} \left[I_p G_p - IG - \frac{k}{k-1} P \frac{dV}{dt} \right] \quad (2)$$

where: V - initial volume;

dV – volume change during movement of the piston;

G_p – the air flow rate into the volume;

G – the air flow rate out of the volume;

I_p – enthalpy of the air flowing into;

I – enthalpy of the air flowing out.

The equation for the density in this volume is written as follows:

$$\frac{\partial \rho}{dt} = \frac{1}{V} \left(G_p - G - \rho \frac{dV}{dt} \right) \quad (3)$$

The equation for determining the temperature in the present volume is written as follows:

$$\frac{dT}{dt} = \frac{dP}{d\rho} = (k-1) \frac{I_p G_p - IG - \frac{k}{k-1} P \frac{dV}{dt}}{G_p - G - \rho \frac{dV}{dt}} \quad (4)$$

A piston often represents the main moving part of pneumopulse device. It is moving under certain changes in conditions inside the device. The equation of piston motion is accounted for a constant component of the pressure forces and friction acting on the piston and variable components, which usually depend linearly on the displacement or velocity of the piston (for example, the force of spring resistance or hydraulic resistance of the extruded fluid):

$$m \frac{d^2 x}{dt^2} = P_1 f_1 - P_2 f_2 - F_{fr} - \varsigma_1 x - \varsigma_2 \frac{dx}{dt} \quad (5)$$

where m - mass of the piston;

x – coordinate of the moving piston;

f_1 – the area of the pressure on one side of the piston;

f_2 – the area of the pressure on the other side of the piston;

P_1, P_2 – pressure, respectively, on the one and on the other side of the piston;

F_{fr} – constant component of the friction force;

ζ_1 – coefficient, which depends on movement;

ζ_2 – coefficient, which depends on the movement velocity.

Thus, the mathematical model of pneumpulse device includes:

- a) the equations describing the quasi-steady overflow of gas between joint volumes;
- b) the equations of thermodynamics to determine the pressure, gas density and temperature for variable mass of the gas in each of the volumes;
- c) the dynamic equations of motion of moving parts of the device, that changes the value of the considered volumes and flow section areas.

The resulting system is a system of ordinary differential equations with initial data, which can be represented in the canonical form

$$\frac{dY_i(t)}{dt} = f(Y_1, Y_2 \dots Y_n) \quad (6)$$

where $i = 1, 2 \dots n$.

For the numerical solution of this system an Euler's method is used. The equation of motion, which is a second order differential equation, is written as two the first order equations:

$$\begin{aligned} \frac{dx}{dt} &= x_1 \\ \frac{dx_1}{dt} &= \frac{1}{m} (P_1 f_1 - P_2 f_2 - F_{fr} - \zeta_1 x - \zeta_2 \frac{dx}{dt}) \end{aligned} \quad (7)$$

Calculations are made by using of modern computer techniques, which allows simulating of the quite complicated unsteady gasdynamic and kinematic processes occurring in high-speed pneumatic devices at involved assumptions.

2.3 Numerical and experimental study of high-speed pneumatic device

Pneumopulse generator PG-0.1/100, designed by the author for cleaning the internal surfaces of pipelines, has been selected as a test high-speed pneumatic unit for investigations. The design of the generator is protected by a patent [12]. A detailed description of the research results can be found in [13].

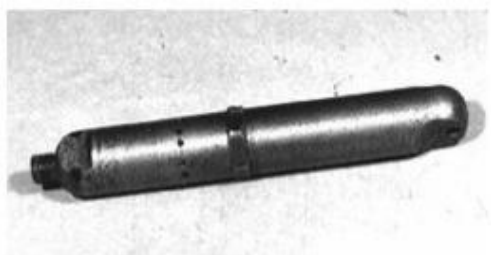


Fig. 4. General view of pneumopulse generator PG-0.1/100

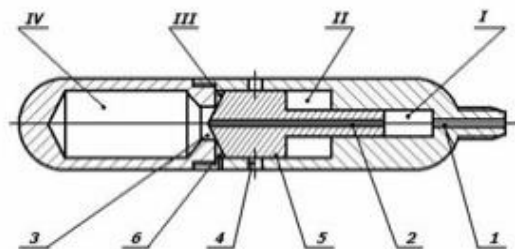


Fig. 5. Working scheme of pneumopulse generator PG-0.1/100

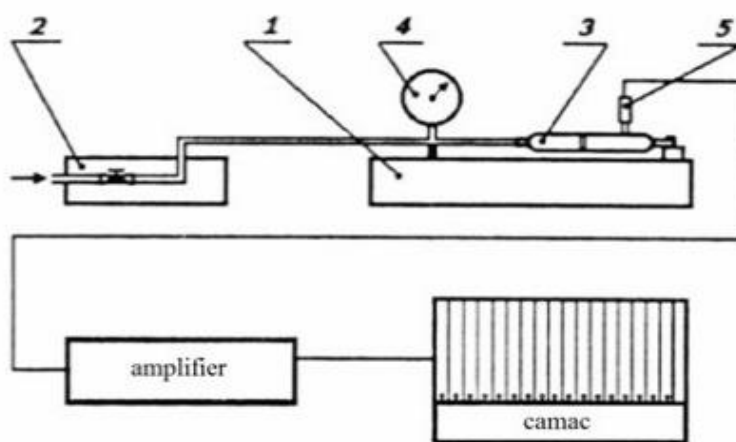


Fig. 6. The experimental setup
1 – frame; 2 – valve; 3 – pneumogenerator PG-0.1/100;
4 – manometer; 5 – pressure sensor

General view of pneumogenerator is shown in the photo Fig. 4. Construction of pneumopulse generator is shown in Fig. 5. The device includes a housing, divided by piston 5 to inlet chamber *I* and accumulative chamber *IV*. The working gas (air or nitrogen) is fed to the inlet chamber *I* from the source of compressed gas (balloon, for example) via a supply channel. Inlet chamber *I* communicated to the storage chamber *IV* through channel 2 in the piston 5. The piston 5 is executed stepwise and it can move under the influence of pressure difference. On the right the force from the inlet chamber *I* and from the chamber *II* acts at the end face of the piston, and on the left – from the storage chamber *IV* and the chamber *III*. The housing has 16 discharging holes 4 through which the air is released from the collecting chamber *IV*, when piston 5 is moving. Flowing air forms intense jets, acting on the surface being cleaned. This design of the generator has high level of efficiency and reliability in comparison with the same device described in [9].

Experimental study of pneumopulse generator was performed using an installation shown in Fig. 6. The analyzed generator 3 was mounted on a frame. The air in the inlet chamber of the generator is fed through the valve 2. After air is supplied the generator automatically starts throwing pulsed air jets with a pulse repetition period of 2 – 3 seconds. During the experiment, we measured the pressure at the entrance to generator P_k (manometer 4) and the changing pressure $P(t)$ in the storage chamber *IV*

of the generator (sensor 5). Experiments were carried out at a pressure at the entrance from $P_k = 1.0$ MPa to $P_k = 6.0$ MPa. Typical results of calculations (solid lines) and experimental (points) are shown in Fig. 7. It shows only one from the calculated parameters – pressure change in the storage chamber *IV* on time, which can be compared with experimental results.

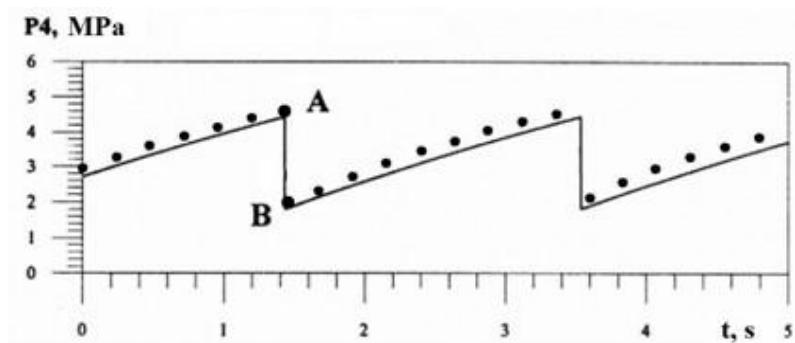


Fig. 7. Change of pressure in the pneumogenerator storage chamber

Before working the pressure in the storage chamber *IV* (see Fig. 5) is equal to atmospheric pressure. After the air supply is switched to the generator input the level of pressure in the inlet chamber *I* increases and causes the piston movement to the left.

In its extreme left position the piston closes exhaust outlet 3 of the storage tank *IV* and air from the input chamber through the channel 2 in the piston is pumped into the storage tank. The area of the exhaust outlet 3 is 10-15% larger than the area of the end surface, so, as the storage chamber *IV* is filling, then force acting on the piston from the orifice area 3 increases and finally exceeds the force acting on the end area of the piston from inlet chamber *I*. At this point, which corresponds to point A in Fig. 7, the piston begins to move to the right and it opens the outlet 3, through which air enters the cavity *III*. The area of influence and force from air pressure resulting from the collecting chamber *IV* increase dramatically and, consequently, the velocity of the piston increases.

Moving piston opens discharging holes 4 and there is a sharp release of air from the storage chamber *IV* in the environment with the formation of strong air jets and shock waves that affect the surface to be cleaned. After resetting the air and reduce the pressure in the storage chamber *IV* the force acting from the inlet chamber *I*, again exceeds the force acting on the opposite side of the piston and the piston begins to move forward.

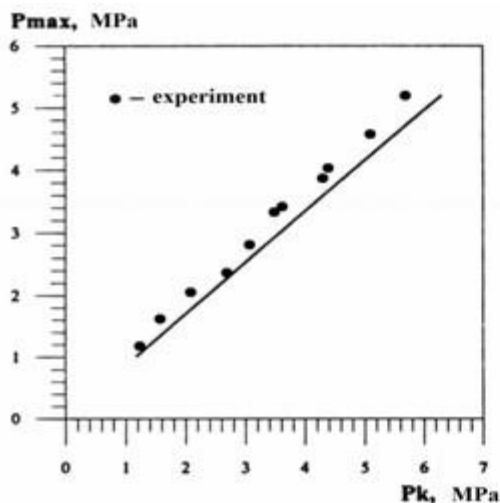


Fig. 8. The maximum pressure of working gas (before of exhaust) according to the pressure in the supply line

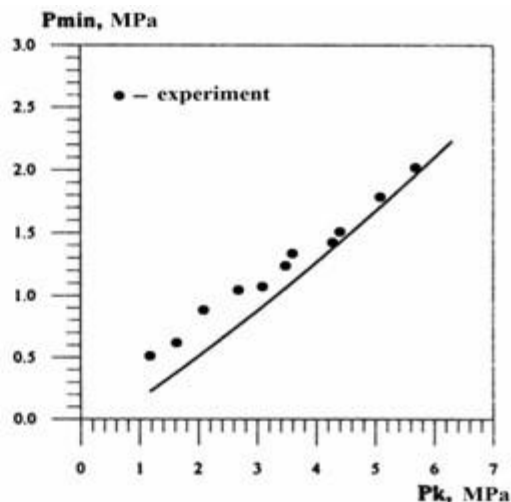


Fig. 9. The minimum remaining pressure of working gas after exhaust according to the pressure in the supply line

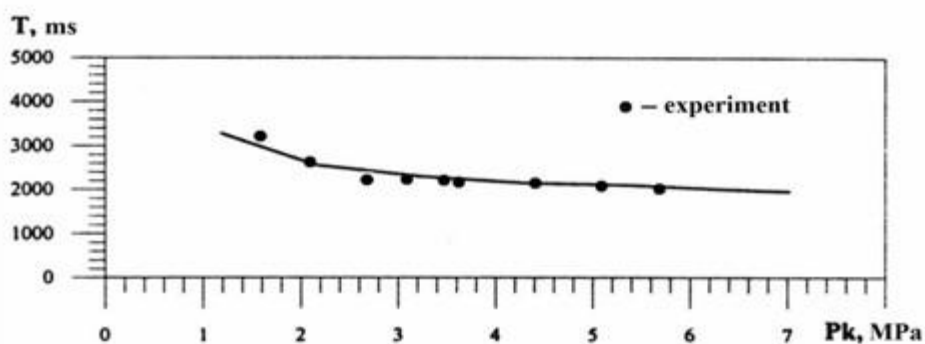


Fig. 10. Duration of the storage chamber filling (the interval between pneumogenerator shots)

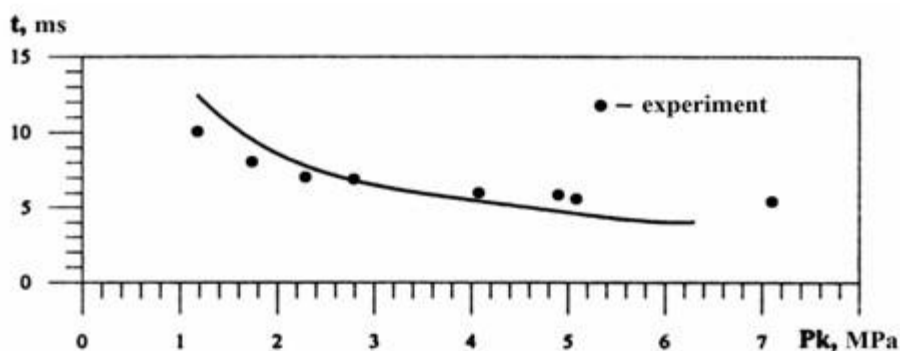


Fig. 11. Duration of the working gas exhaust from the pneumogenerator

At this point in the storage chamber the minimum pressure is reached (point B in Fig. 7). A moving piston closes exhaust holes 4 and outlet orifice 3. It starts refilling of storage chamber and the cycle of the device operation is repeated.

In Fig. 8 – 11 shows a comparison of calculated and experimental values for the general correlations that characterize the work process in pneumopulse generator: the maximum pressure P_{max} , achieved in a storage tank (point A in Fig. 7), the minimum pressure in the storage tank P_{min} (point B in Fig. 7), filling time duration T and the exhaust time t from the pressure at the entrance P_k . It is seen that the calculations accurately reflect the characteristics of the processes occurring during operation of the generator. In particular, the estimated time of filling the storage chamber completely coincides with the experiment at a pressure at the entrance more than 3 MPa. When inlet pressure is below 3 MPa, the time of filling in the calculation is somewhat less because of the unaccounted losses of working gas, which becomes smaller with increasing pressure. The duration of the exhaust in the calculation and experiment decreases with increasing pressure applied to the generator entrance, as the acting forces and, accordingly, the velocity of the piston movement increases. The calculations give underestimated values of the maximum pressure achieved in the storage chamber, and a minimum pressure obtained as a result of air outflowing. However, the behavior of the dependence of P_{max} and P_{min} of the pressure at the generator entrance is the same in the calculations and the experiment.

Good agreement between calculated and experimental results confirms the correctness of a mathematical model of the pneumogenerator working process. The results of calculations and experimental studies have allowed to improve considered pneumopulse generator and to execute the development of other high-speed pneumopulse devices for various practical applications. The same result is described in [14].

2.4 Examples of high-speed pneumatic devices design

In order to solve various technological problems more than 20 different pneumogenerators with high-speed piston valves have been developed by the author. Below one can find short description of some developed pneumogenerators which are widely used for solving of various technological problems.

2.4.1 Pneumopulse generator PG-25/8

In Fig. 12 shows the photograph and assembly drawing pneumopulse generator PG-25/8, which is designed for compressed air energy storage and subsequent release of its as dramatic and powerful impulse to the formation of jets and to carry out technological operations such as clearing bunkers, heat transfer surfaces, ventilation systems, heat exchangers and other devices. The design of the generator is protected by a patent [15].

Housing (prechamber) of pneumogenerator is formed by a cylindrical shell and is used for the accumulation portion of compressed air. The exhaust nozzle in the form of a cylindrical tube is welded to the front and rear end inside the shell. On the outside the tube has a flange with 4 holes that are used for fixing of pneumopulse generator at the facility. The rear end of the tube is closed by plug 2, which the rear flange holds. The movable valve 6 moves in a cylinder of 126 mm in diameter at a distance of 40 mm. Conical liner 5 forms a seat surface for the shut-off valve. Discharge control valve is screwed on a thread M48 * 1.5 in the locking plug and sealed with gaskets. When air applied then discharge valve opens the drop hole with a diameter of 22 mm.

Initially the shut-off valve 6 is in any position. When you turn on the pneumogenerator in action compressed air is supplied from the highway and enters the cavity before the piston valve. Under the action of excess pressure in the cavity the valve moves to the left and sits on a conical liner. In this case the output is blocked path for air from the cavity through an exhaust nozzle. After that, the air

flowing through the clearance between the piston and the cylinder begins to fill the cavity of the prechamber. Prechamber filling lasts within 30 – 60 seconds.

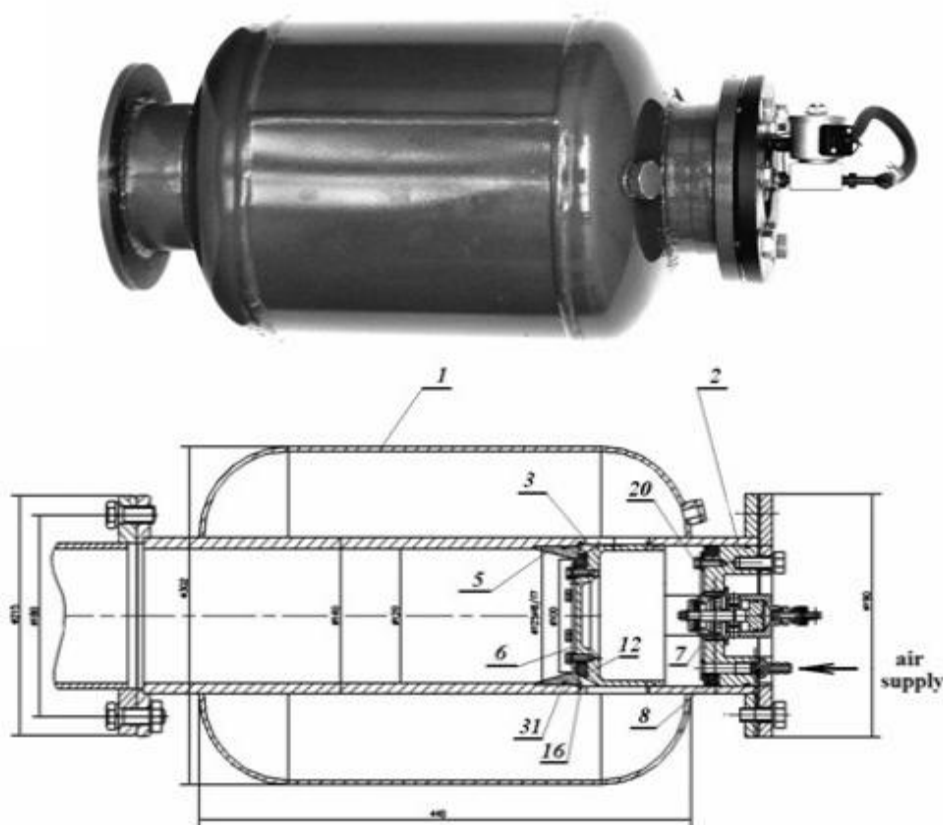


Fig. 12. Pneumopulse generator PG-25/8

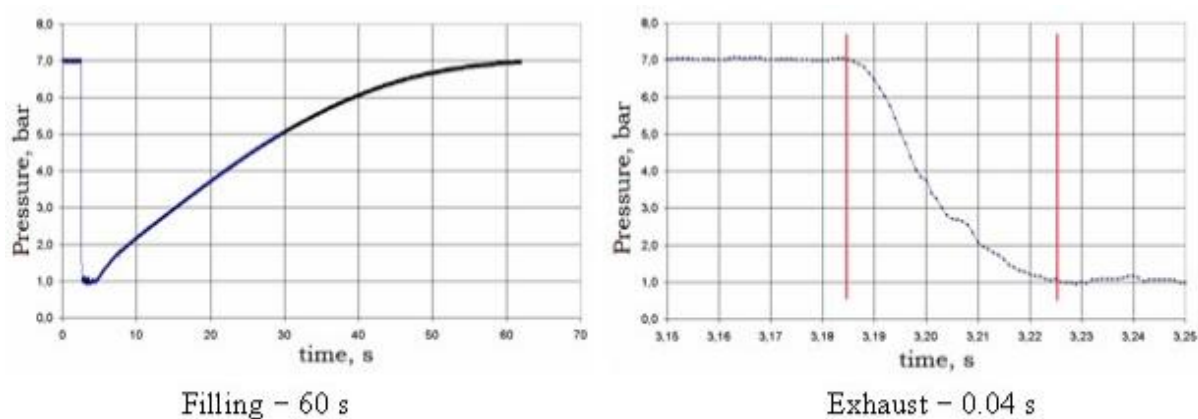


Fig. 13. Measurement of pressure in the storage chamber of pneumopulse generator PG-25/8 in the process of its filling and exhaust

For pneumogenerator operation it is necessary to submit the pressure to the input of dump valve. The discharge valve triggers leading to a sharp decrease in pressure in the cavity before the piston valve 6. The piston moves to the right and stored in prechamber portion of the compressed air is ejected through the exhaust holes in the wall of the tube and then through the exhaust nozzle, carrying out the necessary shock-wave effect. The gas flow rate at the time of the exhaust is about 20 kg/c. After the release of air from the housing 1 charging process is repeated as described above and the operation of the pneumopulse generator can be repeated.

Typical recording of pressure in the prechamber of the generator of time are shown in Fig. 13. It is evident that the process of pneumogenerator filling from atmospheric pressure to a pressure of 7 bar lasts about 60 seconds, and the process exhaust lasts no more than 40 ms. At the same time opening the fast-acting shutter is not more than 4 ms.

Table 1. Main technical characteristics PG-25/8

Prechamber volume, dm ³	25
Period of the prechamber filling, s	30 – 60
Diameter of the exhaust nozzle, mm	120
Operating pressure, bar	3 – 8
Stored energy, kJ	8 – 20
Duration of the exhaust, s	0.05

2.4.2 Pneumopulse generator PG-10/10

In Fig. 14 shows a general view of the pneumopulse generator PG-10/10. Pneumogenerator consists of a prechamber, high-speed auto shutter and exhaust nozzle made of a pipe with diameter of 48 * 3.5. It is thread M48 * 2 on the outer surface of the outlet tube for connection to various devices.

Prechamber is formed by cylindrical shell 3 with two flanges 2 and 7 welded to it. Inside the prechamber exhaust nozzle is in the form of a cylindrical tube that is welded to the front flange 2 and supported by three legs 4. On the back of the flange 7 with pins 9 and compression flange 8 fast-acting shutter 6 is mounted. High-speed shutter design is shown in Fig. 15. The shutter of the generator consists of a housing 5, the liner 15, moving piston 11, restrictor 14, a spring 2 and check valve 3. The shutter is attached to the rear flange 6 with eight pins 7 and slip-on flange 12. Junction between the flange 6 and a shutter housing 5 is sealed with a sealing rubber ring 8. In the valve body screwed socket 9 ($D_N = 4$ mm) to connect the air supply line to the generator. After socket the air on channel of 6 mm in diameter enters the cavity B shut-off valve. The hole in the restrictor 14 at the outlet of this channel allows adjusting the air flow rate to pneumogenerator and, accordingly, the interval between the generator operations.

In the body of shutter motionless liner 15 is set through the rubber O-ring 4, which forms a guide surface for the piston 11. The liner 15 is fixed to the shutter body with plate restrictor 14. The movable piston 11 with a sealing ring 10 can be moved to the right under the action of the spring 2 and under the influence of air pressure in the cavity B and to the left – under the influence of air pressure in the cavity C. For the air supply from the cavity A of a prechamber into the cavity C in the shutter a hole with diameter 2 mm is drilled in normal direction to the axis of the valve. In addition, in shutter body holes 11 are made of 6 mm diameter to exhaust air from the cavity B into the atmosphere. Shut-off valve 3 moves free along a cylindrical guide on the outer surface of the valve body and in the extreme

left position it closes the entrance an exhaust nozzle. For reliable sealing a valve 3 has a rubber gasket 18 which is fixed with metal plates 16 and screws 17. The design provides automatic shutter operation when submitting it to the air pressure from 3 to 10 bars. The principle of the shutter can be seen in Fig. 15. The upper half of Fig. 15 shows the initial position of the moving parts of the shutter before pneumogenerator operation. The bottom half – shows the position of the moving parts during the exhaust process.

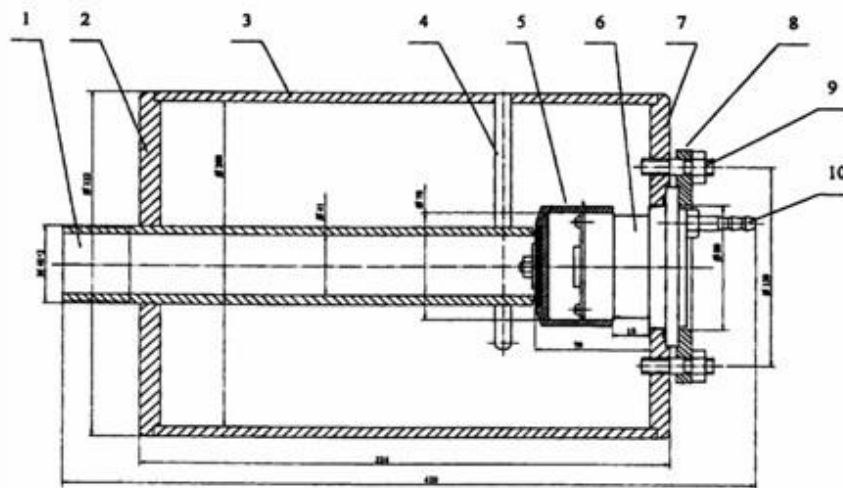


Fig. 14. General view of of the pneumopulse generator PG-10/10
1 – exhaust nozzle; 2 – flange; 3 – shell; 4 – support; 5 – shut-off valve; 6 – the valve body; 7 – flange; 8 – compression flange; 9 – pin; 10 – socket of air supply

Before generator start the movable piston 11 by the spring 2 action is the extreme right position and closes the groove in the liner. When the system is switched on compressed air through the inlet socket 9 enters into the cavity B of shut-off valve 3. Under the action of excess pressure in the cavity B the valve moves to the left and covers an exhaust nozzle entrance 1. After that, the air flowing through the gap between the check valve 3 and the cylindrical guide body 5 begins to fill the cavity A of a prechamber. Increasing pressure in prechamber through the channel is transmitted into the cavity C in the housing 5, and acts on the movable piston 11. At a time when pressure in prechamber reaches approximately 90% of the pressure in the main air supply line to the pneumogenerator, pressure forces acting on the movable piston 11 to the right is higher than the pressure forces acting to the left, and the movable piston 11 begins to move to the left thus opening the discharge of air through a groove in the liner from the chamber B of the shut-off valve 3 in the atmosphere through holes in the body of shutter 5. After that, pressure in cavity B shut-off valve 3 decreases and shut-off valve under the pressure of air in the prechamber moves to the right, opening the inlet nozzle 1. The portion of the compressed air stored in the prechamber is ejected through a nozzle, carrying out the necessary shock-wave effects on the treated object. As a result of air emission from the prechamber a pressure in cavity A is reduced, the spring returns the movable valve to its original position, after which the above-described process of charging and operation the pneumopulse generator automatically repeated with a period of 6 - 10 seconds as long as compressed air supply in pneumogenerator will be blocked.

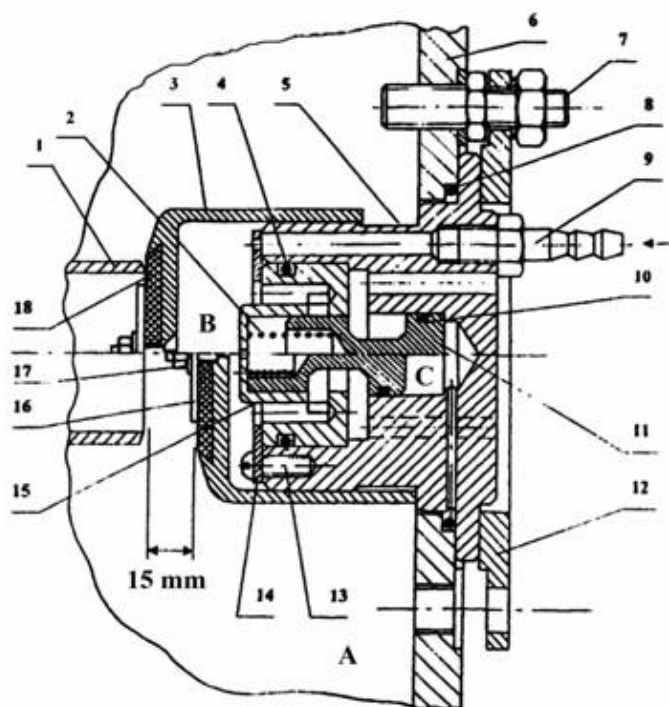


Fig. 15. Fast-action shutter of generator PG-10/10

1 – exhaust nozzle, 2 – spring; 3 – shut-off valve, 4 – ring; 5 – valve body, 6 – rear flange; 7 – pin; 8 – ring; 9 – air socket; 10 – ring; 11 – piston; 12 – compression flange, 13 – screw, 14 – limiter; 15 – insert, 16 – plate, 17 – screw, 18 – seal

Table 2. Main technical characteristics PG-10/1

Prechamber volume, dm ³	10
Period of prechamber filling, s	6 - 10
Weight, kg	8
Diameter of the exhaust nozzle, mm	41
Operating pressure, bar	4 - 10
Stored energy, kJ	7.5 - 25
Duration of the exhaust, s	0.05

2.4.3 Pneumopulse generator PG-1/100

Assembly drawing of pneumopulse generator PG-1/100 is shown in Fig. 16. Pneumogenerator consists of a housing 1, the fast-acting automatic shutter 5 and exhaust nozzle 6, made of a tube with diameter of 25 * 4.0 mm. There is a thread 1" on the outer surface of the nozzle outlet end for connection to various devices.

The body is formed by shell with a wall thickness of 4 mm and two welded flanges. Inside the housing 1 exhaust nozzle 6 is located in the form of a cylindrical tube, hermetically welded to the front flange

and rear flange. At the rear flange with thread M 80 * 1.5 cup 2 is fixed. Inside the cup a piston 5 is placed which closes the nozzle 6 inlet. A fast actuator 3 which triggers the piston 5 is placed consistently with the piston. Handle 4 and socket for compressed air supply are attached to a cup. Actuator 3 serves as a starter for the controlled discharge of air from the cavity before the piston 5. Opening this valve will trigger pneumogenerator.

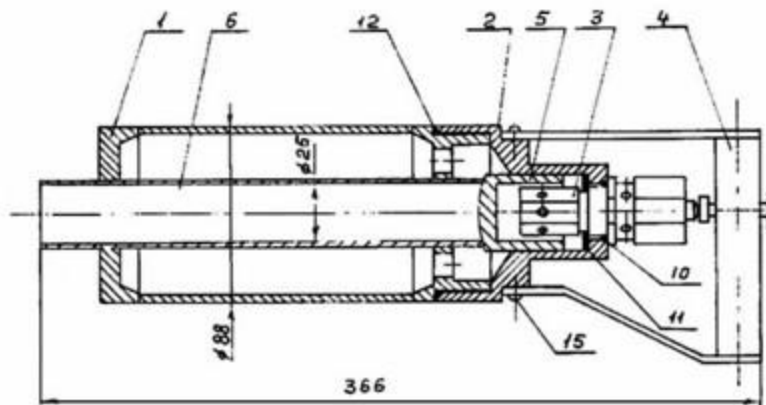


Fig. 16. Pneumopulse generator PG-1/100

1 – housing; 2 – cup; 3 – starter; 4 – handle; 5 – the main piston, 6 – exhaust nozzle, 8 – socket the compressed air supply

Air supply to the pneumogenerator causes an increase in pressure under the piston 5, which immediately closes the inlet of the exhaust nozzle 6. After that, within 5 – 10 seconds there is an accumulation of air in the housing 1. For pneumogenerator actuation it is necessary to press a serving part of the actuator 3, which sharply drops the pressure from the cavity behind the piston 5. Reduction in the pressure causes a rapid withdrawal of the main piston 5 from the inlet nozzle. Compressed air stored in the housing almost immediately ejected through the exhaust nozzle, realizing at the outlet required shock-wave effects on the treated object.

Table 3. Main technical characteristics PG-1/100

Prechamber volume, dm ³	1
Diameter of the exhaust nozzle, mm	25
Operating pressure, bar	10 – 100
Stored energy, kJ	1 – 10
Duration of the exhaust, s	0.02

3. PULSED GAS JETS

Formation of the gas flow pattern at the instantaneous start of gasdynamic impulse device is shown as calculation results in Fig. 17 [16] and as experimental results in Fig. 18. From the beginning spherical shock wave is moving through the undisturbed space, behind which the static pressure increases dramatically. The main parameters that determine the impact of the bow shock, is pressure difference on it, the pulse overpressure behind it and the momentum dynamic pressure of gas immediately behind the wave. After the bow shock wave single-minded focus unsteady gas jet moves, in which there is

alternation of supersonic and subsonic zones separated by shock waves. On the expiration a small time the formation of stream ends and turns from non-stationary into a stationary flow. With a large reserve of the working gas flow will exist for a long time. But as a rule, for impulse creation the pneumopulse devices with fixed and limited volume of working gas are used, so as far as the outflow of gas, its pressure drops to zero and there is the corresponding smooth (quasi-stationary) adjustment resulting jet.

Based on the physical pattern of a pulsed jet, it becomes clear that deposits are consistently faced the shock and the jet gas dynamic effects. Value the contribution of the shock wave and the jet in the process of deposits destruction depends on the amount of storage capacity, the initial pressure in it, the installation start mode, the distance to the treated object, and other factors that determine the parameters of the forming pulse flow.

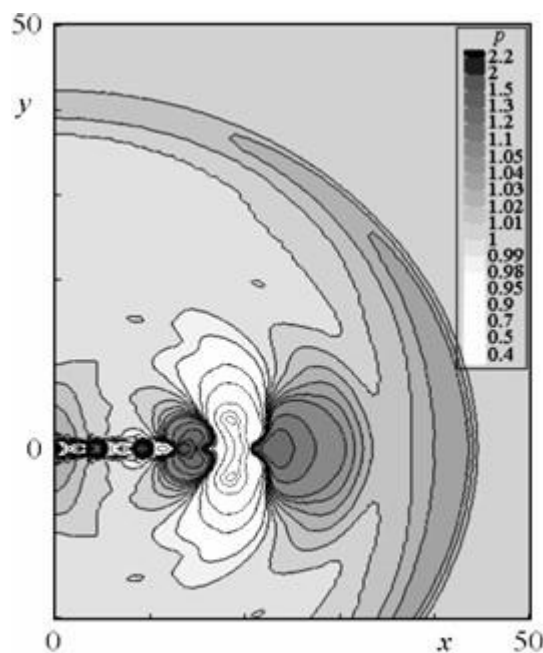


Fig. 17. The pressure distribution during the formation of pulsed jet

3.1 Evaluation of the bow shock wave characteristics

To calculate the pressure difference after bow shock wave, one can use a simple and intuitive computational model. It is assumed that all the available reserve working gas at a pressure equal to the initial pressure P_o in a pulsed gas-dynamic device, is enclosed in a spherical surface, the volume V_o is equal to the volume of storage capacity. The radius of the sphere is:

$$R_0 = \sqrt[3]{\frac{3 \cdot V_0}{4\pi}} \quad (8)$$

The area of a spherical surface:

$$F_0 = 4\pi \cdot R_0^2 \quad (9)$$

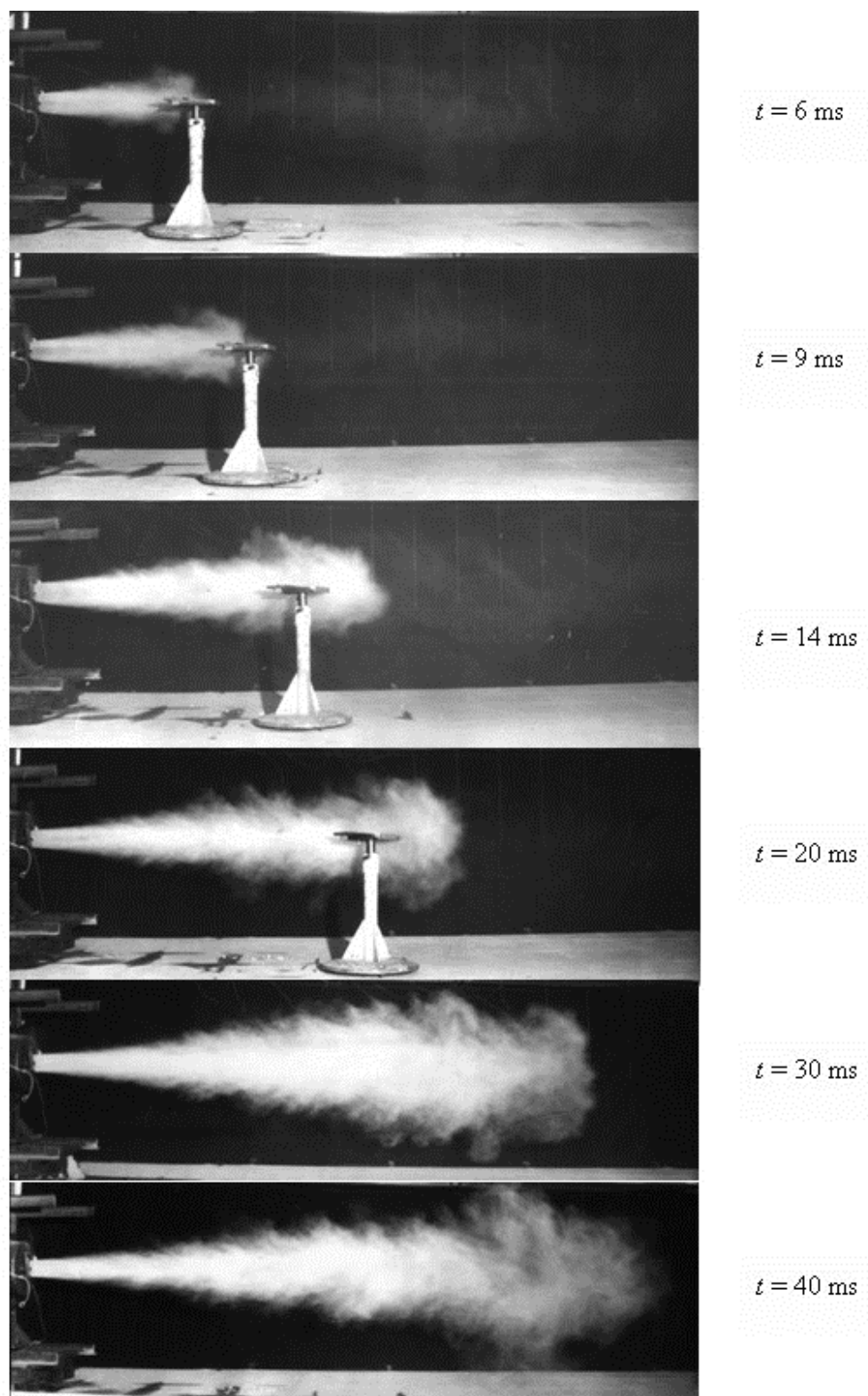


Fig. 18. Visualization of impulse air jet,
arising from the pneumopulse generator

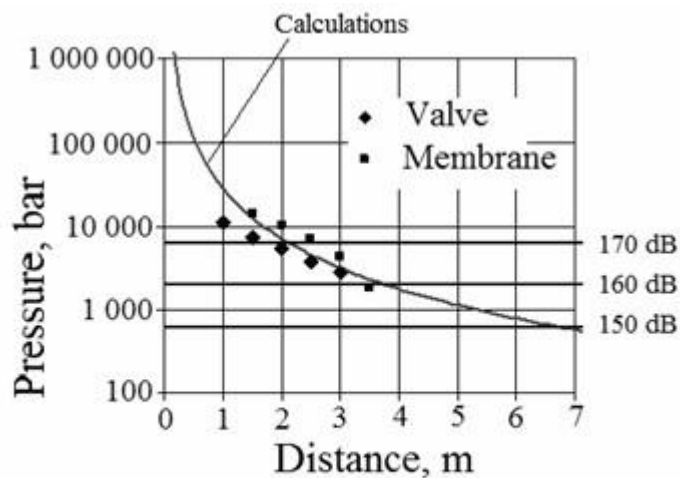


Fig. 19. The pressure behind the shock wave
 $V_0 = 7 \text{ dm}^3$, $P_0 = 2 \text{ MPa}$, $D = 40 \text{ mm}$

The process of spherical surface expanding corresponds to the motion of the bow shock wave. In the process of expansion is assumed that the product (duplication) of pressure on the spherical surface area remains constant. Then at a given radius R the pressure P on the shock wave is:

$$P = P_0 \cdot \frac{R_0^2}{R^2} \quad (10)$$

In Fig. 19 shows the pressure on the shock wave obtained in experimental studies [6] and calculated by the above method. In experiments with membrane almost instantaneous opening of the outlet was provided. For the valve opening time was 3 – 4 ms. In some literature (for example, [7]), sonic pressure equal of 150 dB is recommended as the minimum pressure required for the destruction of ash deposits. We see that in this case, the pressure corresponding more than 150 dB is provided at a distance up to 6.5 m.

3.2 Evaluation of the gas jet characteristics

The stationary outflow of gas from the holes (nozzles) of finite size in free space proceeds with the formation of the gas jet [17]. The main feature of the gas jet is a significant difference between the axial velocity of the gas inside the jet and the gas velocity in the surrounding space, which leads to the formation of the jet boundary layer at the periphery of the jet. For practical purposes single- gas jets are considered or two-phase jets with a low concentration (up to 10% by weight) of liquid or solid particles, which cannot alter the gas-dynamic characteristics of the jet.

3.3 Geometrical characteristics of stationary subsonic jet

A subsonic jet flowing from a nozzle with a uniform velocity distribution into infinite space can be considered as the simplest form. Here gas is moving basically in the direction of the jet (see Fig. 20). At the interface between two streams, as a rule, there are vortexes randomly moving along and across the stream to create mixing due to the exchange of gas from one stream to another. As a result, there is increasing region around the jet with a continuous distribution of velocity, temperature and concentration (in the case of different gases). This area is called the jet turbulent boundary layer. Thickening of the jet boundary layer leads, on the one hand, to increase in cross-section of the excited

flow, and, on the other hand, a decrease of the main stream velocity in cross-section. The site where the original the jet velocity remains constant on the axis is called as initial section of the jet. The length of the initial section of a subsonic jet usually is from 8 to 9 half-width values of the nozzle (or radius for axisymmetric jets). Further thickening of the boundary layer leads to a decrease in velocity on the axis, and a further portion of the jet is the main section. Between the initial and main sections the transition section is located. For engineering calculations the length of transition section shall be taken as zero.

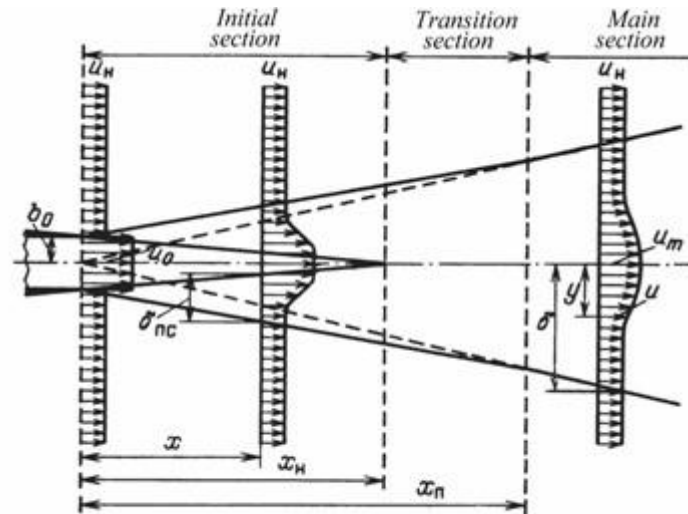


Fig. 20. Scheme of a subsonic jet

The calculation of subsonic turbulent jets is guided by the following basic regularities that follow from theoretical and experimental studies [17]:

1. In any section the jet transverse velocity components are negligible in comparison with the longitudinal components, so they are not considered for practical calculations.
2. The impulse of the jet (momentum) is conserved along the jet and it is equal to the momentum of the jet at the nozzle exit.
3. In cross-section of a subsonic jet static pressure is constant and it is equal to the pressure in the ambient space.

Numerous experiments showed that the growth of the transverse dimension b along the jet length x in a wide range of expiration conditions is almost linear (see Fig. 20) and can be described by a simple formula:

$$b = c \cdot x + b_0 \quad (11)$$

Here $c = 0.27$ for the initial section of the jet and $c = 0.22$ for the main section of the jet.

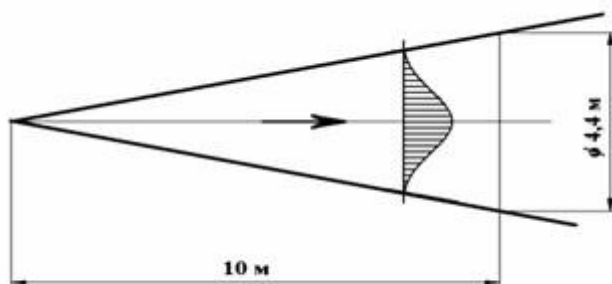


Fig. 21. Computational scheme the main section of the gas jet

For the problems of pneumopulse technologies the main interest is jet characteristics at a large distance from the nozzle. Keeping in mind the short length of the initial section and neglecting diameter of the nozzle, one can use the main portion of the design scheme of the free jet in the form of a cone, starting from the nozzle with an aperture angle $2 \cdot \arctg(0.22) = 24.8$ degrees (see Fig. 21).

The change in velocity u_m on the axis in the main section of axisymmetric jet can be approximated by a simple formula:

$$u_m = u_0 \cdot \frac{12,4}{x/r_0} \quad (12)$$

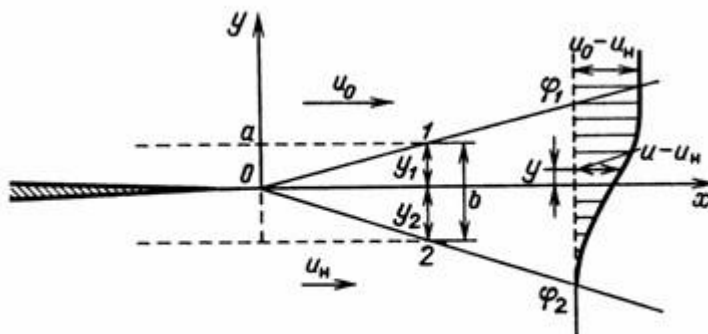


Fig. 22. The scheme of the jet mixing layer

Changing of the excess temperature at the axis for the main section of an axisymmetric jet is approximated by the next formula:

$$\frac{T_m - T_n}{T_0 - T_n} = \frac{12,4}{x/r_0} \quad (13)$$

Changing the dynamic pressure on the axis along the length of the main portion of an axisymmetric jet q_m with respect to dynamic pressure of the jet at the nozzle exit q_0 :

$$q_m = \frac{P}{2 \cdot R T_m} \cdot (u_m)^2 = \frac{P}{2 \cdot R \cdot (12,4 \frac{(T_0 - T_n)}{x/r_0} + T_n)} \cdot \frac{12,4^2 \cdot u_0^2}{(x/r_0)^2} \quad (14)$$

$$\bar{q}_m = \frac{q_m}{q_0} = \frac{12,4^2}{((1 - \frac{T_n}{T_0}) \cdot \frac{12,4}{x/r_0} + \frac{T_n}{T_0}) \cdot (\frac{x}{r_0})^2} \quad (15)$$

Here:

$$q_0 = \frac{P}{2 \cdot RT_0} \cdot (u_0)^2 = \frac{\gamma}{2} PM^2 \quad (16)$$

3.4 Distribution of parameters in the jet transversal cross-sections

Theoretical and experimental results show that the distribution of excess speed (compared to the velocity of gas in the ambient space) in the cross section of the jet boundary layer (or in the main section jet) is universal in nature (see Fig. 22). Simple analytical relationship for the velocity distribution was suggested by H. Schlichting [18]:

$$\frac{u - u_n}{u_m - u_n} = f(\eta) = (1 - \eta^{3/2})^2 \quad (17)$$

Here, $\eta = y / b$ – the distance from the axis of the jet to the point in question, divided by the boundary layer thickness (for the initial section) or by distance from the inner boundary jet to the thickness of the jet (for the main section).

The temperature distribution in the jet can be described by a linear dependence on η :

$$\frac{T - T_n}{T_m - T_n} = 1 - \eta \quad \frac{T_m - T}{T_m - T_n} = \eta \quad (18)$$

The expression for the density of the gas:

$$\rho = \frac{P}{RT} = \frac{P}{R(T_m - \eta(T_m - T_n))} \quad (19)$$

The expression for the dynamic pressure:

$$q = \frac{\rho u^2}{2} = \frac{P}{2 \cdot R(T_m - \eta(T_m - T_n))} \cdot [(u_m - u_n) \cdot (1 - \eta^{3/2})^2 + u_n]^2 \quad (20)$$

For the submerged jet flow velocity in the surrounding space is $u_n = 0$. Accordingly, the dynamic pressure in this case:

$$q = \frac{P}{2 \cdot R(T_m - \eta(T_m - T_n))} \cdot (u_m)^2 \cdot (1 - \eta^{3/2})^4 \quad (21)$$

Dynamic pressure at the jet axis, where $u_n = u_m$:

$$q_m = \frac{P}{2 \cdot RT_m} \cdot (u_m)^2 \quad (22)$$

The distribution of relative dynamic pressure in the cross section of the isobaric jet:

$$\bar{q} = \frac{q}{q_m} = \frac{(1 - \eta^{3/2})^4}{1 - \eta(1 - \frac{T_n}{T_m})} \quad (23)$$

The last expression shows that the distribution of dynamic pressure of the jet cross section depends on the ratio of the temperature in the jet and the surrounding area. At expiration of the cold stream in the space filled with hot gas ($T_n > T_m$), the diagram of the distribution of dynamic pressure is less filled, and the characteristic values of dynamic pressure decrease in 2 – 3 times. The above formulas allow us with sufficient accuracy for practice to estimate the parameters at any point in a gas jet.

4. EXAMPLES OF PNEUMOPULSE TECHNOLOGIES APPLICATION

The results of theoretical research in the field of nonstationary aerodynamics have found practical application in the development of pneumopulse technologies for industry. Process of pneumopulse technologies for industrial applications development includes the following stages:

- consideration of possibilities to improve various processes when using pulsed gas jets;
- optimization of the characteristics of devices used pulsed gas jets;
- development and improvement of actual processes using pneumopulse technologies;
- definition of actual technical and economic performances of technological processes using pneumopulse technology.

Currently pneumopulse technologies developed for the following applications:

- eliminate freezes and sticking on the walls of the bunkers and containers;
- cleaning interior surfaces of pipelines;
- cleaning of heat exchangers of various designs and sizes;
- purification of ventilation devices;
- cleaning of electrical equipment surface;
- cleaning of heating systems of industrial and domestic buildings;
- cleaning of chemical reactors;
- cleaning of heat transfer surfaces in boilers.

Mentioned pneumopulse technologies have been used successfully at the enterprises of energy, coal and steel industry in Russia and abroad. Application experience shows that pneumopulse technologies are more efficient and cost-effective in comparison with others, designed to solution of similar problems. The main economic feasibility of pneumopulse technologies application lays in elimination of the costly labour-intensive and often dangerous manual operations, after which it becomes possible the transition to the real prevention of problems, which gives, finally, a significant increase in efficiency of use of permanent acting equipment.

Below it is a description of some developed pneumopulse technologies.

4.1 Pneumopulse technology for bunkers cleaning

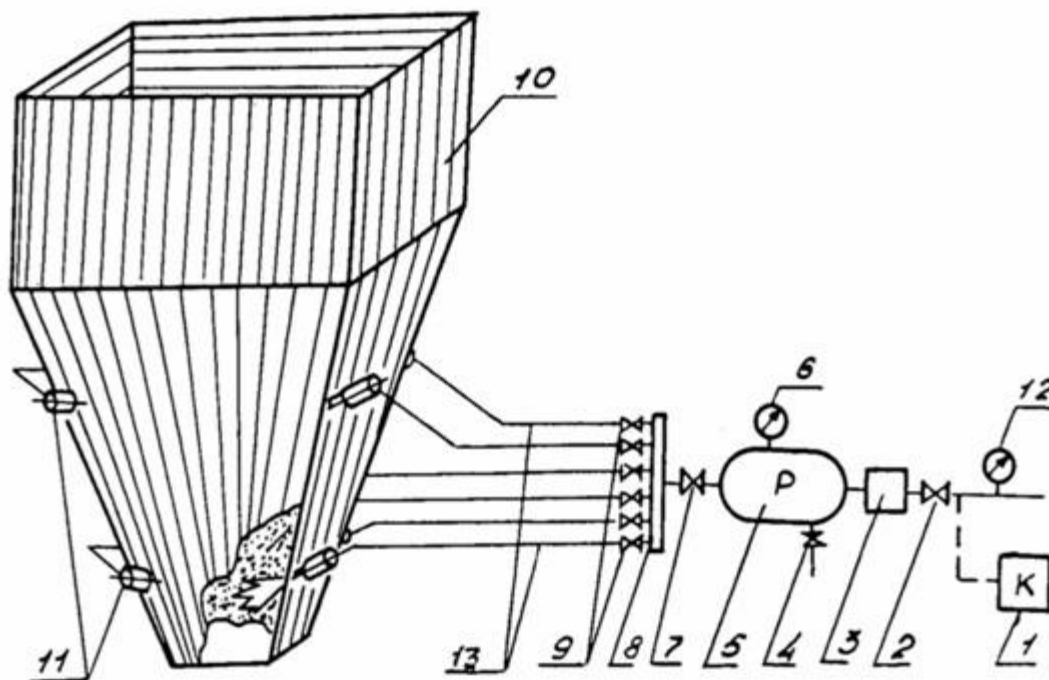


Fig. 23. A pneumopulse system for bunker cleaning
1 – compressor; 2 – shut-off valve; 3 – water and oil separator; 4 – condensate drain valve; 5 – receiver; 6 – manometer; 7 – emergency stop valve; 8 – collector; 9 – supply valves to pneumopulse generators; 10 – bunker; 11 – pneumopulse generators; 12 – pressure control in the network; 13 – network for air distribution

Schematic diagram of bunker cleaning system is shown in Fig. 23. The system is designed to eliminate the adhesion and freezes of bulk materials on the walls in bunkers, regardless of their destination, size and design. On the walls of the bunker 10 located pneumopulse generators 11, this may release pulsed jet into material within a bunker. Typically, this technology used pneumogenerator PG-25/8. Typical number of pneumogenerators in the cleaning system for one bunker is from 2 to 8 units. The air from the compressor of a small power is supplied to the general receiver 5, and then by pipeline 13 to pneumopulse generators.

Prechamber of each generator is filled with air to a pressure level equal to the pressure in the network, after which the air from the prechamber rapidly ejected through the exhaust nozzle to the bunker 10, performing a cleaning operation of the surface. The system can have both manual and automatic (remote) control. Due to high speed of the pneumopulse generator action it is achieved a large value of air flow rate through the nozzle, which ensures high efficiency of bunker surface cleaning [19].

4.2 Pneumopulse technology for pipelines cleaning

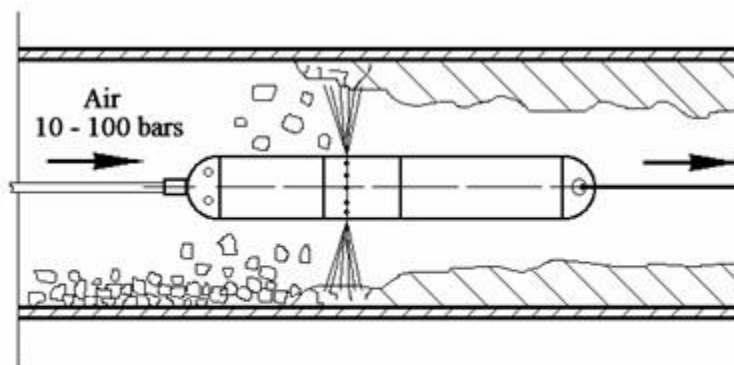


Fig. 24. The scheme of pipeline cleaning with help of pneumogenerator PG-0.1/100

This technology can be used to clean the internal surfaces of pipelines from saline, calcareous, limestone, coal, cement and other deposits of different hardness. One version of the technology developed for cleaning pipes with diameter from 50 mm to 300 mm is based on a pneumogenerator PG-0.1/100 with a diameter of 40 mm and a length of 350 mm. The generator air supply is made through a flexible hose with an inner diameter of 4 mm from the balloon 40 dm³ with compressed air at a pressure of 150 bars. Pneumogenerator works automatically after 1 – 2 seconds and it is pulled inside the pipe by a rope with diameter of 3 – 4 mm (see Fig. 24). This technology has been used for cleaning pipes in the enterprises of power industry [20]. Practical experience has shown that for cleaning of the pipeline of length 50 m it was needed a pneumogenerator working for 10 – 15 minutes with air pressure of 30 – 40 bars. To clear the 100 meters of the pipeline consumed a balloon of compressed air.

The use of the proposed pneumopulse technology for pipes cleaning showed its high efficiency, cost-effectiveness, simplicity of application.

4.3 Pneumopulse technology for industrial and domestic heating systems cleaning

The deposits within the radiators and connecting pipelines are destroyed by shock wave system created in the fluid flowing inside the heating system then they are cleaned and removed by the same liquid. To organize a system of shock waves in the fluid impulse effects of compressed air is used.

An example of cleaning technology is shown in Fig. 25. Here in three-stores building standpipe with radiators 2 is mounted. Water supply is from the top. Visual inspection showed that before cleaning solid deposits of salts and oxides of iron were irregularly distributed along the length in the pipeline and they overlapped cross-section of the pipe up to 70%. Heater sections at the bottom were completely packed with black pasty mass with particles of size 1 – 1.5 mm. At the top of the inner radiator surfaces more dense sediments from a pasty mass of black and brown colours with thickness of 2 – 3 mm have been found.

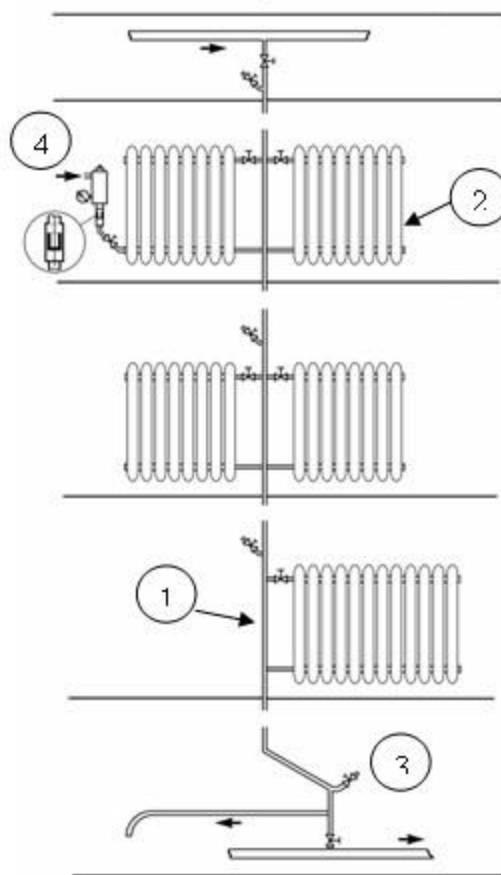


Fig. 25. The scheme of the heating system cleaning

Initially, treatment of standpipe was carried out by using pneumogenerator 4 (type PG-1/100). Compressed air is fed from the standard 40 dm³ balloon with an initial pressure of 130 – 140 bars. Several shots from pneumopulse generator were fired in the standpipe with the initial pressure in the 50 – 60 bars through the nozzles 3 at a constant water flow. Most of the sediments deduced running water as a thin black particles with dimensions of 0.1 mm. Discharge water flow rate measurement showed that the flow of water through the standpipe after cleaning increased by 4.5 times.

To clean the heating radiators pneumogenerator was mounted on special plugs 4 in the heating devices. Cleaning technology included five shots at each radiator with the air pressure 30 – 60 bars. After this pneumopulse generator was disconnected and the quality of cleaning was estimated visually. The internal cavity of the radiator was almost clean. After cleaning the regular plugs were installed on the heating device and the heating system was put in working condition. Water supply under pressure to 5 bars showed that the system integrity and the tightness of all joints were not violated.

4.4 Pneumopulse technology for heat exchangers cleaning

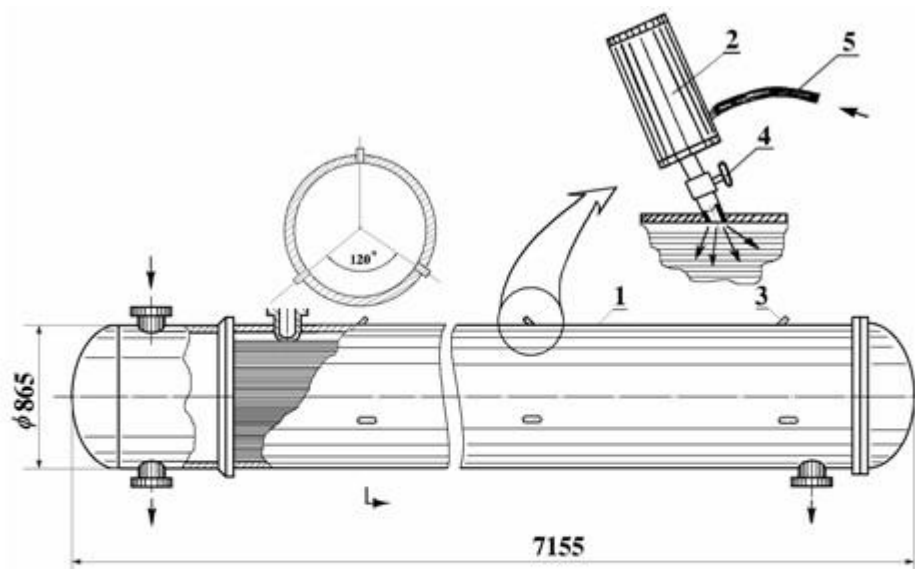


Fig. 26. Scheme of heat exchanger 800 TNG cleaning
1 – heat exchanger body, 2 – pneumopulse generator PG-1/100; 3 – outlet $\frac{3}{4}$ ",
4 – ball valve, 5 – air supply pipe

The task of cleaning the heat exchanger is solved by pneumopulse generator PG-1/100, which throws into water-filled heat exchanger a short-term jet of compressed air. Inside the heat exchanger a shock wave creates that propagates in the fluid and destroys the fat. Number of points of supply air jets, their orientation and duration of the treatment process are determined by practical consideration, depending on the configuration of the heat exchanger and the strength characteristics of the sediments.

To clean the sediment of thickness from 2 to 5 mm in the space between the tubes of heat exchanger 800 TNG, nine pipes with diameter of 20 mm welded to the body heat exchanger were used, as shown in Fig. 26. Through the each tube 10 – 15 shots were carried out from pneumogenerator with a storage chamber volume of 1 dm³ at air pressure of 20 bars. Heat exchanger cleaning process has occupied near two hours.

3.5 Pneumopulse technology for convective surfaces of boilers cleaning

While operating boilers a big problem is the formation of slag and ash, which are deposited on the heat transfer surfaces and violate the normal operation of the boiler [21]. The relevance of pneumopulse technology development for the boilers treatment was caused by, primarily, large absolute value of losses with a decrease in boiler power, as well as high cost and lack of efficiency of existing treatment means. Experience has shown that the use of pneumopulse devices enables the creation of highly effective, safe and remotely operated treatment systems.

Investigations the possibilities of pneumopulse devices for boilers cleaning were started in the ITAM SB RAS since 1992 [22-23]. Initially laboratory experimental studies were carried out of the pulsed

jets effectiveness. As a result of the jet impact to models of sediment with different strengthens the decisive influence of the shock wave in the process of deposits destruction was shown in comparison with impact of the gas jet dynamic pressure. Data also were obtained on the effect of the pneumopulse device design parameters on the characteristics of generated shock waves. It is established that the effectiveness of the impact to a considerable extent is determined by the orientation of the shock wave relative to the destroyed sample. The actual designs remotely operated pneumopulse generators were developed with stored energy of compressed gas to 100 kJ. Design of multi nozzles device was suggested, which significantly increase the area of the cleaned surface by 1.5 times. A significant increase in the efficiency of cleaning is achieved by organizing the simultaneous action of several pulse generators.

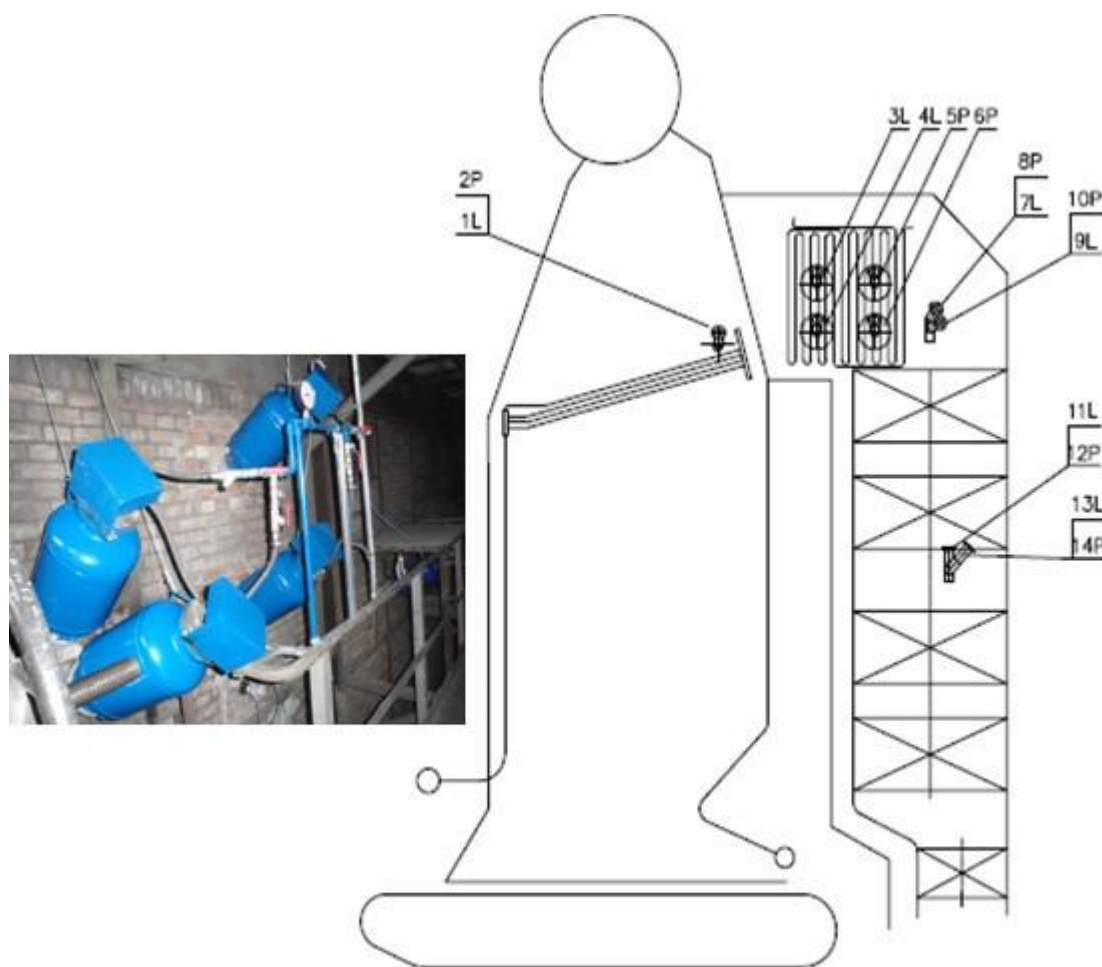


Fig. 27. Placement of generators PG-25/8 at the boiler OR-32 [24]

Currently pneumopulse treatment systems are installed on the boilers of different capacity. As an example, Fig. 27 shows the installation of 14 pneumogenerators PG-25/8 on the average power boiler OR-32 at sugar factory in Poland [24]. During the three months of operation the boiler heating surfaces remained operational and clean, despite the severe operating conditions caused by the ever-changing modes of operation. The average productivity was of 30 tons of steam per hour. The temperature of exhaust gases was 15 degrees lower than in neighbouring similar boiler.

In Fig. 28 shows a treatment system of 18 pneumogenerators PG-25/8 for cleaning the boiler super heater PK-38 (Russia) with capacity 240 tons of steam per hour [25]. The system is automatically enabled in accordance with a chosen technology regime. Analysis of the results has shown that the treatment system has provided the boiler with an average capacity of 225 tons of steam per hour for 3 months. In this period the screens of super heater remained operational and clean, and the temperature of exhaust gases decreased by 10 degrees.

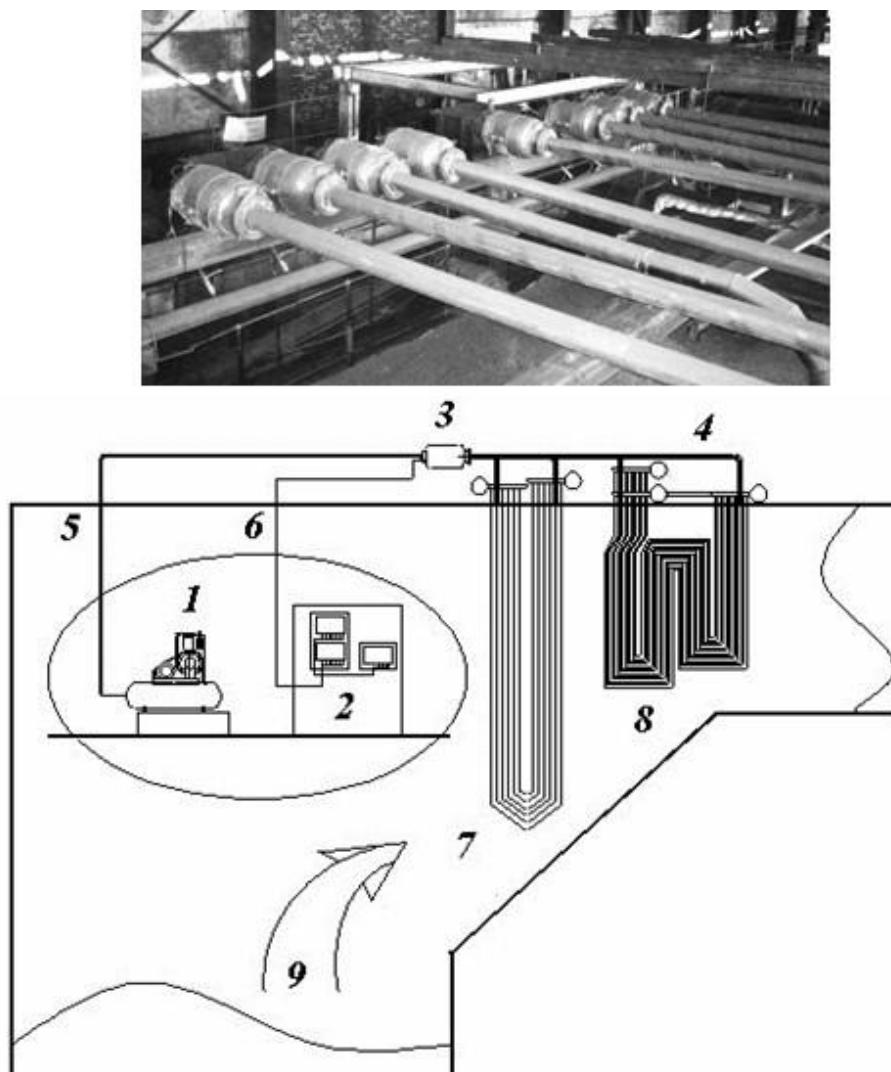


Fig. 28. Placement of pneumopulse cleaning system at the boiler PC-38 [25]
1 – compressor; 2 – control system; 3 – pneumogenerator PG-25/8; 4 – pipelines for jet pulse feeding; 5 – compressed air; 6 – control electric line; 7 – the primary superheater screens; 8 – secondary screens; 9 – direction of furnace gases

Considered pneumopulse cleaning systems for boilers of small, medium and high capacity are based on modern achievements in the field of unsteady gas dynamics and their characteristics are unique in

the world. Upon successful completion of the testing period similar systems could be recommended for replication in power industry in Russia and abroad.

CONCLUSIONS

Accumulated experience suggests that the use of pneumopulse technologies based on reliable fast-acting pneumopulse devices can lead to a substantial modernization of known technological processes, or even to the appearance of essentially new industrial technologies.

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